Brief Reports

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Searching for *CP* violation in "charge-blind" jets

Marc Kamionkowski
Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637
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Although it is difficult to determine the identity of the parent parton of hadronic jets produced in high-energy particle-antiparticle collisions, "charge-blind" jets, those where such information is not determined, may still be used to obtain *CP*-violating correlations. In this paper, I provide a general method for determining which correlations may be used as signatures of *CP* violation.

In the twenty-five years since its discovery,[1] only the very delicate K^0-$\overline{K^0}$ system has yielded an observable signal of *CP* violation. Although the standard model and simple extensions can accommodate *CP* violation,[2,3] its fundamental origin is still a mystery, and parameters describing *CP* violation must be determined by experiment.

Here we investigate a promising approach introduced by Donoghue and Valencia[4–6] where one searches for *CP*-violating correlations among jets in particle-antiparticle collisions without distinguishing the identity of the parent parton. Although these effects are expected to be small, and precise determinations of jet properties are difficult, much work has been done on quantifying jet observables for several proposed models for *CP* violation; however, to date, no complete demonstration that the correlations considered are actually signatures for *CP* violation has been provided. The goal of this Brief Report is to provide such a demonstration.

To find genuine *CP*-violating correlations, I generalize the technique of Bernreuther *et al.*[6] by working with cross sections instead of form factors and by avoiding reference to a specific intermediate state. I then give examples of such asymmetries and discuss "*T*-odd" and "*P*-odd" quantities and distinguish these from *CP*-violating asymmetries.

Let us focus our attention on electron-positron collisions; the generalization to $p\bar{p}$ collisions is straightforward. Consider the process $e^+e^-\to$hadrons. In the center-of-mass frame, the initial state is

$$|I\rangle=|e^+(\mathbf{p},i)e^-(-\mathbf{p},j)\rangle\equiv|\mathbf{p},ij\rangle$$

which is characterized by the relative momentum $\mathbf{p}$ and the spin state (i and j) of the electron and positron. Under the operation of *CP* this state transforms as

$$CP|I\rangle=-|\mathbf{p},ji\rangle\ ;$$

since, under *P*, the momentum is inverted and the relative intrinsic parity of electron and positron is odd while under *C*, the electron and positron are interchanged. In a realistic experiment, the initial state is not necessarily a pure spin state. We describe the initial ensemble by the density-matrix operator

$$\hat{\rho}\equiv|\mathbf{p},ij\rangle\rho_{iji'j'}\langle\mathbf{p},i'j'|\ .$$

Now, let us impose the condition that the initial state be *CP* blind. This is accomplished by demanding that

$$(CP)^{-1}\hat{\rho}(CP)=\hat{\rho}\ . \tag{1}$$

This implies that the polarization vectors of the electron and positron, $\mathbf{S}_-$ and $\mathbf{S}_+$, are the same, $\mathbf{S}\equiv\mathbf{S}_-=\mathbf{S}_+$; however, the spin density matrix is not necessarily fully determined by this polarization vector.

Now, let us imagine that we observe final states with three jets and for a simple example, let us assume that we know from its "fatness" that one is a gluon jet[7] with momentum $\mathbf{k}$ while the other two are quark and antiquark jets; however, we do not distinguish between quark and antiquark since the experiment is charge blind. Below, similar results will be obtained for the case for which the gluon is indistinguishable from the quarks. The quark jets are labeled by $\mathbf{k}_1$ and $\mathbf{k}_2$ where $|\mathbf{k}_1|>|\mathbf{k}_2|$. The final state is then

$$\begin{aligned}|F_>\rangle&=|\bar{q}(\mathbf{k}_1,\alpha)q(\mathbf{k}_2,\beta)g(\mathbf{k},\epsilon)\rangle\\&\equiv|\mathbf{k}_1,\mathbf{k}_2,\alpha,\beta,\epsilon\rangle\ ,\\ \mathbf{k}&=-(\mathbf{k}_1+\mathbf{k}_2)\ ,\end{aligned}$$

if the antiquark has a greater momentum than the quark, or

$$|F_<\rangle=|\bar{q}(\mathbf{k}_2,\beta)q(\mathbf{k}_1,\alpha)g(\mathbf{k},\epsilon)\rangle$$
$$\equiv|\mathbf{k}_2,\mathbf{k}_1,\beta,\alpha,\epsilon\rangle$$

if the quark has a greater momentum than the antiquark. Here, α, β, and ϵ are the internal quantum numbers of the quarks and gluon. Under CP, this state transforms as

$$CP|F_>\rangle=-|-\mathbf{k}_2,-\mathbf{k}_1,\beta,\alpha,\epsilon\rangle \tag{2}$$

and

$$CP|F_<\rangle=-|-\mathbf{k}_1,-\mathbf{k}_2,\alpha,\beta,\epsilon\rangle \ .$$

The matrix element for the transition from the initial state to a given final state is

$$\langle\mathbf{k}_1,\mathbf{k}_2,\alpha,\beta,\epsilon|\tau|\mathbf{p},ij\rangle$$

for final states where the antiquark is more energetic than the quark, and

$$\langle\mathbf{k}_2,\mathbf{k}_1,\beta,\alpha,\epsilon|\tau|\mathbf{p},ij\rangle$$

otherwise. The cross section for the three-jet final state as a function of the charge-blind variables $\mathbf{k}_1$ and $\mathbf{k}_2$ is given by

$$d\sigma(\mathbf{k}_1,\mathbf{k}_2)=\mathrm{Tr}\sum_{\alpha,\beta,\epsilon}[\langle\mathbf{k}_1,\mathbf{k}_2,\alpha,\beta,\epsilon|\tau\hat{\rho}\tau|\mathbf{k}_1,\mathbf{k}_2,\alpha,\beta,\epsilon\rangle+\langle\mathbf{k}_2,\mathbf{k}_1,\beta,\alpha,\epsilon|\tau\hat{\rho}\tau|\mathbf{k}_2,\mathbf{k}_1,\beta,\alpha,\epsilon\rangle] \ , \tag{3}$$

where the sum is over the unobserved quantum numbers. In order to determine the consequences of CP invariance, insert the identity

$$1=(CP)^{-1}(CP)$$

into Eq. (3). Since, for a CP-invariant interaction,

$$(CP)^{-1}\tau(CP)=\tau \ ,$$

the result is

$$d\sigma(\mathbf{k}_1,\mathbf{k}_2)=d\sigma(-\mathbf{k}_1,-\mathbf{k}_2) \tag{4}$$

as a consequence of Eq. (1). Therefore, any violation of this condition signals CP violation.

Using the same approach, the results may be generalized. If one uses n jets with momenta $|\mathbf{k}_1|>|\mathbf{k}_2|>\cdots>|\mathbf{k}_n|$, and no determination of the identity of the parent parton is made, it is found that a CP-invariant interaction must satisfy

$$d\sigma(\mathbf{k}_1,\mathbf{k}_2,\ldots,\mathbf{k}_n)=d\sigma(-\mathbf{k}_1,-\mathbf{k}_2,\ldots,-\mathbf{k}_n) \ . \tag{5}$$

Thus, most generally, the two ingredients necessary for the observation of CP violation in charge-blind jets are beams characterized by a density matrix satisfying Eq. (1) and a cross section in terms of the jet momenta, $\mathbf{k}_1,\mathbf{k}_2,\ldots,\mathbf{k}_n$ violating Eq. (5).

Let us now consider specific examples of terms in $d\sigma$ that will yield CP-violating correlations. Table I contains an inexhaustive list of angular correlations and their behavior under CP. First, as discussed by Donoghue and Valencia,[4] if $J_1\equiv\mathbf{k}_1\cdot\mathbf{S}\times\mathbf{p}$, then an asymmetry between the number of events with $J_1>0$ and those with $J_1<0$ signals CP violation. This is expected to occur, for example, in a multiple-Higgs-boson model for which CP is violated by the interference between diagrams differing by the exchange of a Z^0 and a neutral Higgs boson.[8] In this case, top-quark jets would most likely give an observable signal since Higgs-boson couplings are proportional to the mass of the quark to which they are coupled. Two similar CP-odd quantities are $(\mathbf{k}_1+\mathbf{k}_2)\cdot\mathbf{S}\times\mathbf{p}$ and $(\mathbf{k}_1-\mathbf{k}_2)\cdot\mathbf{S}\times\mathbf{p}$. In all three of these correlations, the quark momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ contain no information about C; it is the direction of the electron-positron relative momentum $\mathbf{p}$ that determines a particle-antiparticle asymmetry with charge-blind jets.

TABLE I. Correlations that violate CP and those that do not violate CP (OK). $\mathbf{p}$ is the electron-positron relative momentum, $\mathbf{k}_1$, $\mathbf{k}_2$, and $\mathbf{k}_3$ are the momenta of the fastest, second fastest, and third fastest jets, and $\mathbf{S}$ is the common polarization vector of the electron and positron beams.

Sample angular correlations Term	CP character
$(\mathbf{k}_1\pm\mathbf{k}_2)\cdot\mathbf{S}\times\mathbf{p}$	CP violating
$[(\mathbf{k}_1\pm\mathbf{k}_2)\cdot\mathbf{S}\times\mathbf{p}][\mathbf{p}\cdot(\mathbf{k}_1\pm\mathbf{k}_2)]$	OK
$\mathbf{p}\cdot(\mathbf{k}_1\pm\mathbf{k}_2)$	CP violating
$\mathbf{p}\cdot\mathbf{k}_1\times\mathbf{k}_2$	OK
$(\mathbf{p}\cdot\mathbf{k}_1\times\mathbf{k}_2)[\mathbf{p}\cdot(\mathbf{k}_1\pm\mathbf{k}_2)]$	CP violating
$\mathbf{S}\cdot\mathbf{k}_1\times\mathbf{k}_2$	OK
$(\mathbf{S}\cdot\mathbf{k}_1\times\mathbf{k}_2)[\mathbf{p}\cdot(\mathbf{k}_1\pm\mathbf{k}_2)]$	CP violating
$\mathbf{k}_1\cdot\mathbf{k}_2\times\mathbf{k}_3$	CP violating

Now consider a P-violating and motion-reversal-violating quantity, $J_2\equiv\mathbf{p}\cdot\mathbf{k}_1\times\mathbf{k}_2$. If one argues that under T, momenta are reversed, invokes the CPT theorem, and concludes that an asymmetry in J_2 signals CP violation, then Eq. (4) is contradicted. As is well known, the problem is that final-state interactions can mimic T violation. If the derivation of Eq. (4) is carried out for T instead of CP, Eq. (2) must be changed because T transforms an *in* state to an *out* state and vice versa. These two sets of states are connected by the S matrix and therefore depend on the final-state phase shifts.[9] It is often said that "T-odd" final-state interactions are expected to be small for jets, and this is corroborated by one-loop calculations of $e^+e^-\to q\bar{q}g$ in massless QCD (Ref. 10); however, the same calculation for massive quarks yields a nonzero "T-odd" $\mathbf{S}\cdot\mathbf{k}_1\times\mathbf{k}_2$ correlation.[11] Since QCD is a T-invariant theory, this correlation must be a final-state interaction effect and it is clear that observables odd under motion reversal should *not* be generally used as signatures of T (or CP) violation.[12]

One should keep in mind that the standard $SU(3)\times SU(2)\times U(1)$ model with Kobayashi-Maskawa (KM) mixing is expected to give unobservably small asymmetries of the type discussed here. The reason is that in this model, CP violation arises from W couplings to quarks and two different KM couplings are required;

therefore, the required Feynman diagrams must be of order G_F^2 or higher. Thus, the search for *CP*-violating signatures based on the failure of Eqs. (4) or (5) could be very interesting should any such effects exist.

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[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).

[2]M. Kobayashi and K. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[3]S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).

[4]J. F. Donoghue and G. Valencia, Phys. Rev. Lett. **58**, 451 (1987); **58**, 243 (1988).

[5]M. B. Gavela, F. Iddir, A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Phys. Rev. D **39**, 1870 (1989).

[6]W. Bernreuther, U. Löw, J. P. Ma, and O. Nachtmann, Z. Phys. C **43**, 117 (1989).

[7]The differentiation of the parent parton is discussed by P. Mattig, Phys. Rep. **177**, 141 (1989).

[8]H. Cheng, Phys. Rev. D **34**, 1397 (1986).

[9]For a discussion of final-state interaction effects and *T*-violation mimicry, see R. G. Sachs, *The Physics of Time Reversal* (University of Chicago Press, Chicago, 1987), pp. 105–118.

[10]J. G. Körner and G. Schuler, Z. Phys. C **26**, 559 (1985).

[11]K. Fabricius, I. Schmidt, G. Kramer, and G. Schierholz, Phys. Rev. Lett. **45**, 867 (1980).

[12]See Gavela *et al.* (Ref. 5), for a discussion of how to distinguish final-state-interaction effects from true *T*-violating effects in jet aplanarities.